PREDICTION OF FRACTURE TOUGHNESS SCATTER IN HEAT AFFECTED ZONES (HAZ) OF WELDED JOINTS

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Welding, inspection, repairs and weldment related failures play an important role in the economics of many industries. Carbon-Manganese steels are widely used in welded structures. For low temperature applications, it is essential to maintain a good toughness level in the welds. In a first part, the local criteria approach is extended to situations involving heterogeneous materials. In a second part, numerical computations are carried out in order to explore the influence on the probability of failure of different parameters such as : notch position, HAZ width, Mismatch conditions, etc. This comprehensive approach allows a better understanding of the toughness behaviour of heterogeneous materials.

INTRODUCTION

Welding, inspection, repairs and weldment related failures play an important role in the economics of electric power generating plants, offshore oil industry, pipelines, etc. For the offshore industry, forming and welding represent 57% of the cost of the construction and even more important proportion of the maintenance costs (Lessels et al. (1)). A better comprehension of the structural integrity of weldments would give rise to many advantages. The first one is a better level of security of the structure with a particular emphasis on probabilistic analysis. The second advantage is the reduction and simplification of pre-production qualification criteria. Last, but not least, a simplification of the assessment procedure of a given structure is in view. Indeed, a predictive model will give a better choice of the welding parameters and of the base metal satisfying a certain requirement against fracture.
A model based on the local approach is being developed (Sainte Catherine et al. (2)) and the main results are reported here. The second part of this

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article consists in numerical computations carried out in order to explore the influence of some parameters on the failure probability as a function of the stress intensity factor. These parameters are the width of the HAZ (Heat Affected Zone), the notch position, the HAZ properties and the mismatch conditions. This is a comprehensive method which allows the toughness behaviour of heterogeneous materials to be understood.

LOCAL CRITERIA AND MATERIAL PARAMETERS

The aim of this part is to measure the mechanical properties and the local criteria of the different zones of the weld (base metal, HAZ and weld).

Base material
The base metal used in this study is a normalised 40 mm thick plate of carbon manganese (C-Mn) steel. Chemical composition is given in table 1. This steel has a ferritic-pearlitic banded structure with a mean ferritic grain diameter of 20 μm.

	C	Mn	Si	P	S	Al	Ni	N	Cr	Mo
Base Metal	170	1141	290	7	2	20	252	9	160	53

Table 1 : *Chemical composition of the base steel (in 10^{-3} weight percent).*

Simulated Heat Affected Zones (HAZ)
The microstructures of the HAZ were simulated on normal testing specimens. Thermal cycles were defined in order to simulate those experienced in HAZ during the real welding process (Devillers et al. (3)). These simulations represent the welding conditions simply using one or more (up to three) temperature peaks. Each peak is characterised by the maximum temperature reached and by the time elapsed between the two temperatures 700°C and 300°C (Δt_{300}^{700}) during cooling. Thermal cycles carried out for this study are only representative of a monopass weld process with a peak temperature equal to 1300°C and Δt_{300}^{700} of 300, 100, 50 and 20 s. HAZ 100 will correspond in the following text to a HAZ with a maximum temperature of 1300°C and a Δt_{300}^{700} equal to 100 s. These thermal simulations are very precise since they were carried out with a Gleeble RPI 1500 simulator (see Ferguson (4)).

Weld metal
The weld metal elaboration is described with the multipass weld part but some mechanical properties are given in the following paragraph.

Mechanical properties

For the base metal, the tensile properties were measured in the transverse direction at room temperature and below (Sainte Catherine et al. (2)). Results are given in table 2 for room temperature in which σ_{ys} is the yield stress, UTS the ultimate tensile stress, A% the total elongation and Z% the reduction in area of cross section. TK 28J is the transition temperature defined for an energy of 28 J. The charpy energy at the ductile plateau is also given.

	Tensile Properties (20°C)				Charpy V		Local Criteria	
	σ_{ys} (MPa)	UTS (MPa)	A (%)	Z (%)	TK 28J (°C)	Duc. (J)	m	σ_u (MPa)
Base Metal	356	540	33.0	74.0	-70	173	15	2700
1300°C+300s	489	656	25.5	65.9	-20	> 135	16	2487
1300°C+ 100s	583	766	20.7	70.8	20	200	16	2970
1300°C+50s	905	1059	15.1	62.6	10	> 80	16	3780
Weld Metal	451	571	23.2	79.0	-	-	16	2500

Table 2 : *Mechanical properties of base metal, simulated HAZ and weld metal at room temperature.*

Local criteria for cleavage fracture

In this study, the cleavage criterion proposed by Beremin (5) is used. It is based on the Weibull statistic :

$$P_F = 1 - \exp\left[-\left(\frac{\sigma_W}{\sigma_u}\right)^m\right] \qquad (1)$$

where m is the Weibull exponent, σ_u is the critical cleavage stress of the material. σ_u has not the same definition as that given by Ritchie, Knott and Rice (6) because size effects are included. It could be defined as the cleavage stress for an arbitrary volume V_0, here taken as (100 µm)^3. The cleavage stress for a larger volume can be evaluated using the Weibull statistics : $\sigma_u^m \cdot V_0 = \sigma_c^m \cdot V$, where σ_C is the cleavage stress for a volume V corresponding to a particular geometry. σ_W is called the "Weibull stress" ; it is an integration of the principal stress computed in the plastic region at the crack tip :

$$\sigma_W^m = \int_{V_p} \sigma_I^m \frac{dV}{V_0} \qquad (2)$$

In this approach, the material resistance to cleavage fracture is characterised by two parameters (m and σ_u). These material parameters were determined

with notched tension specimens. Full details concerning this determination can be found in Beremin (5).
Results for the base metal and for the simulated HAZ are given in table 2. Following the local approach, toughness can be evaluated for different probability levels by :

$$K_{IC} = \left(\frac{V_0 \cdot \sigma_u^m \cdot Ln(1/(1-P_F))}{\sigma_y^{m-4} \cdot B \cdot C_m} \right)^{1/4} \qquad (3)$$

where P_F is the failure probability, B the specimen thickness of SENB specimen and C_m a nondimensionnal function of n (strain hardening coefficient) and m. In equation (3), the temperature dependence of K_{IC} is described only by the yield stress dependence. The material parameters σ_u and m are assumed temperature independents. Using this procedure, toughness transition curves for the base metal and the simulated HAZ can be predicted.

INFLUENCE OF THE HAZ PROPORTION ON TOUGHNESS

The objective of this part is to compare the toughness measurements and predictions for an homogeneous brittle zone of well controlled dimension which has been produced with an electron beam.

SENB specimen elaboration

Following the experimental techniques developed by Kaplan and Devillers (7), we used an electron beam in order to obtain a small brittle zone (5 mm). The angle of inclination was equal to 30°, in order to control the width of the fusion line (figure 1). Kaplan and Devillers (7) have demonstrated that the molten metal in that case is comparable to a brittle zone. An equivalent value of Δt_{300}^{700} can be evaluated as 50 s.

Figure 1 : *SENB specimen (W=30mm, B=15mm, a/W=0.5) with a brittle zone intercepting the notch, (original technique developed by Kaplan and Devillers (7)).*

Toughness results and probability of survival

We measured K, J and CTOD critical values at different temperatures on SENB specimens. The experimental results are given in figure 2 where K_J is derived from J integral.

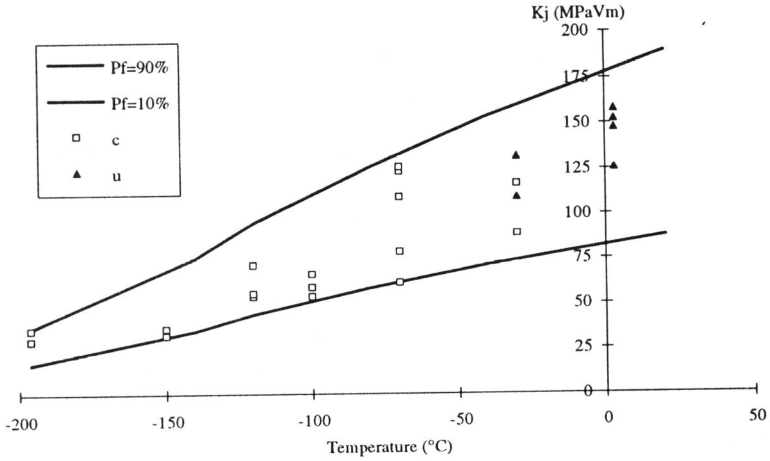


Figure 2 : *Toughness as a function of temperature (points : experimental results, continuous lines : theoretical prediction).*

The continuous lines give the predicted scatter band of toughness based on the following theoretical approach. The integrity of a structure is assured only if each of its elements j remains intact (weakest link assumption), consequently we can write :

$$P_s^{tot.} = \prod_j (P_s^j) \tag{4}$$

with :

$$P_S = 1 - P_F \tag{5}$$

By combining equations (3) and (4), considering only two zones (the base metal (BM) and the HAZ), we obtain :

$$P_S^{tot.} = \exp\left(-\frac{\sigma_{y\_BM}^{m-4} \cdot B_{BM} \cdot K_{IC}^4 \cdot C_{m\_BM}}{V_0 \cdot \sigma_{u\_BM}^m} - \frac{\sigma_{y\_HAZ}^{m-4} \cdot B_{HAZ} \cdot K_{IC}^4 \cdot C_{m\_HAZ}}{V_0 \cdot \sigma_{u\_HAZ}^m} \right) \tag{6}$$

where B_{BM} equal 10 mm and $B_{HAZ} = 5$mm. Due to the weakest link assumption, K_{IC} is also the stress intensity factor for the different materials. As a loading parameter, it is common to the two zones and we could write the following equation :

$$K_{IC} = \left(\frac{Ln \dfrac{1}{1-P_F}}{\dfrac{\sigma_{y\_BM}^{m-4} \cdot B_{BM} \cdot C_{m\_BM}}{V_0 \cdot \sigma_{u\_BM}^{m}} + \dfrac{\sigma_{y\_HAZ}^{m-4} \cdot B_{HAZ} \cdot C_{m\_HAZ}}{V_0 \cdot \sigma_{u\_HAZ}^{m}}} \right)^{1/4} \quad (7)$$

In this relation, K_{IC} must be considered as the toughness of a bimaterial. The theoretical results given by equation (7) are compared to the experimental ones in figure 2. The agreement is very good. This approach is able to give not only a prediction of the dependence of the toughness on temperature but also on the amount of brittle zones intercepted by the crack front. To do this, only the ratio B_{HAZ}/B_{BM} needs to be modified.

MULTIPASS WELD

In this part, we studied a multipass weld. The toughness was also measured on single edge notched bend specimens and compared with predicted values.

Specimen elaboration

Submerged Arc Welding (SAW) was carried out with wire electrodes in tandem configuration on a K-geometry. The input energy was 40 kJ/cm and the interpass temperature was 130°C. There was no post-heating or heat treatment after welding. Some of the welds were instrumented with thermocouples in order to measure the thermal cycle. Experimental values of Δt_{300}^{700} were about 100 s.

Forty SENB specimens were machined in these multipass welds. Fatigue crack fronts were perpendicular to the metal plate and included in the HAZ on the vertical side of the K-weld geometry.

Toughness results

CTOD was measured at -40, -20 and 0°C following BS 5762. Each specimen has been metallographically observed. The initiation sites were identified and the proportion of CGHAZ encountered by the crack front was measured. Experimental results are plotted in figure 3. Then, the theoretical predictions are derived from equation (7). They are represented by continuous lines in figure 3. A schematic view of the model is given in the upper right part of this figure. It does not correspond strictly to the experimental, it is only a representation of what is taken into account by the equations. Despite this very simple model, only two zones (BM and HAZ) are taken into account, the prediction agrees fairly well with experimental results. A very encouraging point is that this theoretical approach seems to be conservative but not in excess.

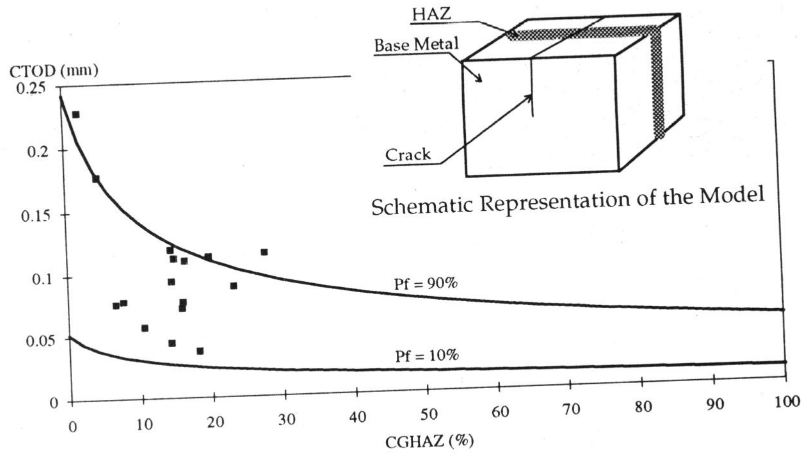


Figure 3 : *Comparison of experimental and theoretical CTOD results (respectively points and lines) for the multipass weld at -40°C.*

NUMERICAL COMPUTATION APPROACH

In this paragraph, we will have a look at the case of 2D computations on a SENB specimen with more than one material. The objective of these numerical computations is to understand how toughness will be affected by heterogeneous material. This analysis is limited here to cleavage fracture.

Material laws and mesh geometry

The materials laws for -40°C have been used. 2D finite element computations are carried out for SENB specimens (W=40mm and a/W=0.5) in plain strain condition. The specimen could be composed of three materials as indicated in figure 4. The following parameters are studied :

- width of HAZ (1.5, 2.5 and 5.0 mm),
- notch position (middle of HAZ, BM-HAZ or HAZ-WM interfaces),
- HAZ properties (HAZ 300, HAZ 100, HAZ 50),
- mismatch conditions (M=1.25, 1.00 and 0.75) with $M = \sigma_y^{WM} / \sigma_y^{BM}$.

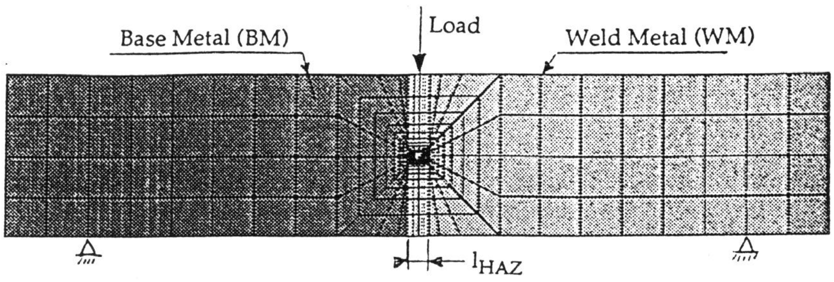
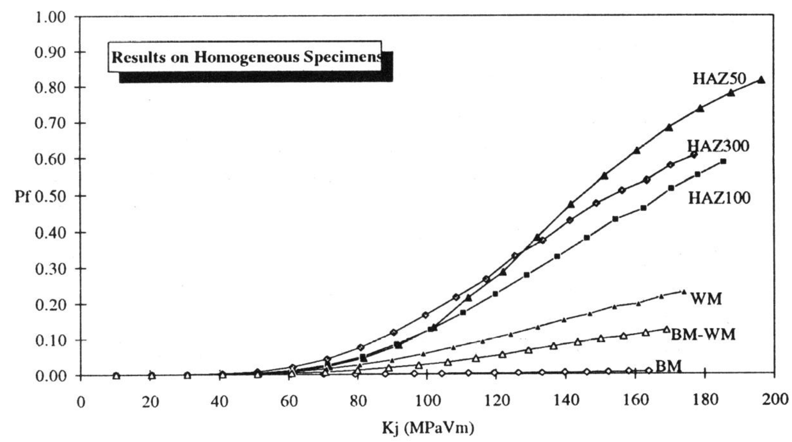
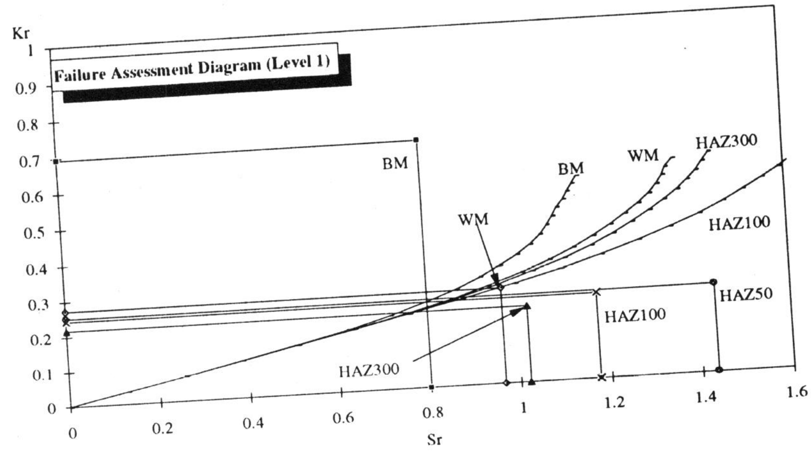


Figure 4 : *Meshing of SENB specimen with three materials.*

Presentation of the results
A reference case has been a computation in which the base metal properties have been used everywhere in the computed specimen (case BM). We will present the results in two different ways : failure probability as a function of toughness level and Failure Assessment Diagram (FAD) level 1. Figure 5 gives preliminary results for homogeneous materials.
The HAZ have a greater general yield limit load (vertical line) and a smaller brittle level than base metal (horizontal line correspond to 2.5% of failure probability (Gordon (8))). The loading curves are represented and give an intersecting point with the corresponding FAD. As can be seen, the load limit is attained first for base metal. But, for HAZ the 2.5% failure probability level is generally achieved before the load limit.



a) Failure probability as a function of toughness level.



b) Failure Assessment Diagram (FAD) at Level 1 and loading curves.

Figure 5 : *Results for homogeneous materials and for a crack at the interface between base and weld metals (BM-WM) without HAZ.*

Influence of HAZ width

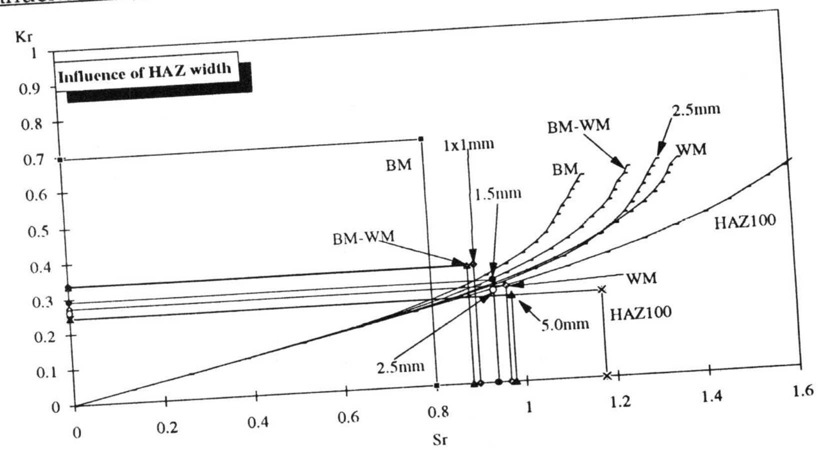


Figure 6 : *Influence of HAZ width on FAD.*

Four cases of HAZ widths (5.0, 2.5, 1.5 mm and 1x1 mm) have been simulated. In all these cases, the notch was located in the middle of HAZ 100 and the mismatch condition was M=1.25. The results are given in terms of FAD in figure 6 and compared to the base metal, HAZ 100, weld metal and interface WM-BM.
The influence of HAZ is very strong and increases with width. The load limit increases and the cleavage level decreases. That will clearly affect the overall capacity of the structure and brittle failure could easily take place.

Influence of notch position, HAZ properties and mismatch conditions
In this article, only the main observations for these parameters are summarised.
The notch position in HAZ is influential, particularly if there is another brittle zone in close proximity. In fact, when the crack is located at the interface between HAZ and weld metal, the fracture probability is higher. This kind of crack located at the interface between base metal and HAZ is very often observed experimentally.
The mechanical properties of HAZ give best results in the case of short cooling time and high yield strength where a screen effect in term of stresses can be observed. It means that low energy weldment processes have to be recommended.
Three cases of mismatch (M=1.25, 1.00, 0.75) have been studied. They correspond to over-, even- and under-matching cases. The results show that for cleavage fracture, the lower tensile properties of the zones adjacent to HAZ have to be recommended. This means that a value of M=0.75 is the best choice from a cleavage point of view. It is obviously not the case for ductile fracture where a strain localisation has to be avoided. Finally, the best choice is probably the even-match case or a little over-match (1.10) to prevent the occurrence of the under-match case due to the scatter in yield strength.

CONCLUSIONS

In this article, two main objectives are under completion. The first is to achieve a predictive approach in order to understand all toughness aspects of heterogeneous materials such as welds. It has been clearly demonstrated that the cleavage toughness variation and its scatter can be predicted as a function of the different zones intercepted by the crack front.
The second objective of this work is devoted to the simplification of the procedure in order to include it in a design code. This has begun with numerical computations which allow the construction of failure assessment

diagrams. This approach is very convincing but experimental evidence (wide plate tests and the corresponding predictions) is needed.

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